## A Thermodynamic Entropy Based Approach for Fault Detection and Prognostics of Samples Subjected to Corrosion Fatigue Degradation Mechanism

**Mohammad Modarres** 

Presented at ESREL2015, Zurich Switzerland September 8, 2015 Center for Risk and Reliability Department of Mechanical Engineering University of Maryland, College Park, MD 20742, USA



COPYRIGHT © 2015, M. Modarres

## Objectives

- Description of degradation mechanisms and resulting damages within the irreversible thermodynamics framework
- Improved understanding of the coupled mechanisms
- Development of an entropic corrosion-fatigue damage model
- Confirmatory testing of the corrosion-fatigue model
- Investigation of applications to structural integrity and reliability assessment
- Search for applications to Prognosis and Health Management (PHM) of structures



## Introduction

- The common definitions of damage are based on observable *markers of* damage which vary at different geometries and scales.
  - > At the macroscopic level: Observable markers of damage (e.g. crack size, pit densities, weight loss) vary.



Fatigues markers used: reduction of elasticity modulus, variation of hardness, cumulative number of cycle ratio, reduction of load carrying capacity, crack length and energy dissipation



[1] J. Lemaitre, "A Course on Damage Mechanics", Springer, France, 1996.

# Entropy and Damage

- Entropy provides a unified and broad measure of damage in terms of energy dissipations of multiple irreversible degradation processes
- Entropy enables us to model multiple competing degradation processes contributing to damage
- Entropy is independent of the path to failure for a system ending at similar total entropy at the time of failure
- Entropy accounts for synergistic effects arising from interactions between multiple degradation processes
- Entropy applies to all scales



## Damage and Entropy



#### Damage $\equiv$ Entropy

• An entropic theory follows:

#### Failure occurs when the total entropy exceeds the entropic-endurance of the system

- Entropic-Endurance is the capacity of the system to withstand entropy
- Entropic-Endurance of the same systems are equal
- Entropic-Endurance of different systems are different
- Entropic-Endurance is measurable and involves stochastic uncertainties



## **Total Entropy Generated**

• The variation of *total entropy*, *dS*, is in the form of:

 $dS = d \uparrow r S + d \uparrow d S$ 

 $d\uparrow r S$  = exchange part of the entropy supplied to the system by its surroundings through transfer of matters and heat:

 $d \uparrow r S/dt = -\int \uparrow \Omega$   $J \downarrow s A$ 

 $d\uparrow dS =$  dissipative part of the entropy produced inside of the system:  $dS = d\uparrow rS + d\uparrow dS$ 

 $d \uparrow d S/dt = \int \uparrow V \# \sigma dV$ 

- Divergence theorem leads to:  $\rho ds/dt + \nabla J ls = \sigma$ , where, *S* is the specific entropy per unit mass.
- The evolution trend of the damage, *D*, according to our theory is dominated by the entropy generated:

 $D|t \sim \int 0 \uparrow t \equiv [\sigma|X \downarrow i(u), J \downarrow i(u)] du$ J=entropy flux,  $\sigma$ =entropy generation/unit volume/unit time

 $d \uparrow r S$ 

Surroundings

System

 $d \uparrow d S$ 

> 0

Ω

 $\sigma > 0$ 

V

### Total Entropy Generated (Cont.)

• Entropy generation  $\sigma$  involves a thermodynamic force,  $X \downarrow j$ , and an entropy flux,  $J \downarrow i$  as:

$$\sigma = \Sigma \downarrow i, j X \downarrow i J \downarrow i (X \downarrow j); \quad (i, j=1, ..., n)$$

Note that when synergy between multiple dissipation / damage processes exist Onsagar reciprocal relations define forces and fluxes. For example for Fatigue (f) and Corrosion (c)

 $J \downarrow c = L \downarrow cc X \downarrow c + L \downarrow f c X \downarrow f \qquad \text{and} \qquad J \downarrow f = L \downarrow f c X \downarrow c + L \downarrow f f X \downarrow f$ 

• The entropy generation due to important dissipation phenomena: Heat energy Diffusion energy Plastic deformation energy

 $\sigma = 1/T \uparrow 2 \mathbf{J} \mathbf{J} q \cdot \nabla T - \mathcal{L} \mathbf{k} = 1 \uparrow \mathbf{n} \text{ Chemical reaction energy External fields energy } / T$  $\mathcal{L} \mathbf{j} = 1 \uparrow \mathbf{r} \ v \mathbf{j} \ A \mathbf{j} + 1/T \ \mathcal{L} \mathbf{j} = 1 \uparrow \mathbf{h} \ c \mathbf{j} \mathbf{m} \mathbf{J} \mathbf{m} (-\nabla \psi)$ 

 $\int \ln (n = q, k, and m)$  = thermodynamic fluxes due to heat conduction, diffusion and external fields, T = temperature,  $\mu \downarrow k$  = chemical potential,  $\nu \downarrow i$  = chemical reaction rate,  $\tau$  = strengthermodynamic,  $\tau = strengthermodynamic, fields, T = temperature, <math>\mu \downarrow k$  = chemical affinity,  $\psi$  = potential of the external field,  $\frac{1}{2}$  and  $\frac{1}{2}$  = chemical affinity,  $\psi$  = potential of the external field,  $\frac{1}{2}$  = chemical affinity,  $\psi$  = potential of the external field,  $\frac{1}{2}$  = chemical affinity,  $\psi$  = potential of the external field,  $\frac{1}{2}$  = coupling constant [1, 2].

[1] D. Kondepudi and I. Prigogine, "Modern Thermodynamics: From Heat Engines to Dissipative Structures," Wiley, England, 1998.

## Entropy Generation in CF

• Contribution from corrosion activation over-potential, diffusion over-potential, corrosion reaction chemical potential, plastic and elastic deformation and hydrogen embrittlement to the rate of entropy generation [1]:

Electrochemical	
$\bigcup_{J \neq M} dissipations \qquad (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, a + J \downarrow M, c \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \downarrow a ct, c - I \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \ (J \neq M, a \ z \downarrow M \ (J \neq M, a \ z \downarrow M \ F E \downarrow M \ (J \neq M, a \ z \downarrow M $	+ <b>J</b> \$0,a
$z\downarrow 0 FE\downarrow 0\downarrow act, a + J\downarrow 0, c z\downarrow 0 FE\downarrow 0\downarrow act, c ) Difference dissinct the set of the s$	usion
$+1/T (J \downarrow M, c z \downarrow M FE \downarrow M \downarrow conc, c + z \downarrow O F J \downarrow O, c E \downarrow O \downarrow conc, c)$	)
+1/T ( $\mathbf{J} \mathcal{M} \alpha \alpha \mathcal{M} A \mathcal{M} + \mathcal{J} \mathcal{M}, c (1 - \alpha \mathcal{M}) A \mathcal{M} + \mathbf{J} \mathcal{J} O, a u$	Chemical reaction
JJM,a(1) dissipations	dissipations
$+1/T \epsilon \downarrow p: \tau \prec$ Hydrogen embrittlement dissipation	
$+\sigma \downarrow H$	

T = temperature,  $Z \downarrow M =$  number of moles of electrons exchanged in the oxidation process, F = Farady number,  $\prod_{e \in SI_{T_{e}}} A$  and  $J \downarrow M, C =$  irreversible anodic and cathodic activation currents for oxidation reaction,  $J \downarrow O, a$  and  $J \downarrow O$  and  $I \downarrow O$  an

# **CF** Simplifying Assumptions

- Entropy flow due to heat exchange is negligible 1
- 2. Diffusion losses are eliminated assuming well mixed solution
- 3 Effect of diffusivity and concentration of hydrogen at the crack surface excluded for Aluminum alloys under cyclic loading in the sodium chloride solution (Mason confirms that in fatigue loading > 0.001 Hz less time for diffusion and accumulated hydrogen exists)
- The Ohmic over-potential effect was minimal by placement of the Luggin 4. capillary close to the working electrode
- 5 Activation over-potential has been considered to be result of Mechano-chemical effect.

 $\sigma = 1/T (I \downarrow M, \alpha \alpha \downarrow M A \downarrow M + I \downarrow M, c (1 - \alpha \downarrow M) A$  $\int M + J \downarrow O, \alpha \alpha \downarrow O A \downarrow O + J \downarrow O, c (1 - \alpha \downarrow O) A \downarrow O)$  Corrosion current-potential hysteresis

**Corrosion current-potential hysteresis** 

where,  $A = \sum i \nu i \mu i$  is mechano-chemical affinity induced by mechanochemical potential  $\mu \downarrow i = \mu \downarrow i + z \downarrow i F(E - E \downarrow corr)$ .

 $+(1/T \epsilon \downarrow p: \tau+1/T YD)$ 

## Corrosion Fatigue Experimental Set up

- Fatigue tests of Al 7075-T651 are performed in 3.5% wt. NaCl aqueous solution acidified with a 1 molar solution of HCl, with the pH of about 3.5, under axial load controlled and free corrosion potential
- Specimen electrochemically monitored via Gamry potentiostat using Ag/AgCl reference electrode maintained at a constant distance (2 mm) from the specimen, a platinum counter electrode, and the specimen as the working electrode
- Stress von Mises (WCS) [MPa] Loadset LoadSet1 : AL7075-ULTINATE2M
- Digital image correlation (DIC) technique used to measure strain



## Entropy Generation in CF

• Total entropy is measured from the hysteresis loops resulted from fatigue (stress-strain) and corrosion (potential-electrical) in each loading cycle



## Entropy to Failure

- Similarity of the total entropy at the time of failure supports the proposition of the entropic theory of damage offered in this research
- More tests needed to reduce the epistemic uncertainties and further confirm the theory



## Interplay of corrosion and fatigue entropy

- Reducing maximum stress allows more time for corrosion thus increasing contribution of corrosion to total entropy
- See ratio of entropy from corrosion to the total entropy versus ratio of entropy from fatigue to the total entropy



COPYRIGHT © 2015, M. Modarres

## Using Entropy for Reliability Analysis

• A dimensionless damage index can be defined as:

 $D = \gamma \downarrow d - \gamma \downarrow d \downarrow 0 / \gamma \downarrow d \downarrow E - \gamma \downarrow d \downarrow 0$ 

where  $\gamma \downarrow d$  is the volumetric dissipative entropy  $\gamma \downarrow d \downarrow 0$  is the initial entropy and  $\gamma \downarrow d \downarrow E$  in an entropic-endurance value

 Material, environmental, operational and other types of variability in degradation impose uncertainties on the total entropy/ cumulative damage, *D*



 $R(t) = \int T \downarrow_{\mathcal{C}} \uparrow \infty = g(t) dt = 1 \int D \downarrow_{\mathcal{F}} \uparrow \infty = f(D|t) dD$ 



Time

t

14

, the reliability function

g(t)=Time to failure distribution

f(D|t)=Normalized entropy to failure distribution

#### Entropic-Based Reliability Assessment



### Application of the Entropic PHM Framework

• Proposed PHM framework has been used to predict the RUL of Al samples.



#### An Example of RUL Prediction

- *kNN* is a non-parametric classification method
- Fault level (FL) determined from the output of the *kNN* classification
- An anomaly was acknowledged from FL



## Conclusions

- A thermodynamic theory of damage proposed and tested
- Applications to reliability and structural integrity assessments explored
- The proposed theory offered a consistent and science-based model of damage and allowed for the incorporation of all underlying dissipative processes
- Entropy generation function derived and evaluated for corrosion-fatigue degradation mechanism in terms of leading dissipative processes
- Entropic corrosion-fatigue degradation model experimentally studied and supported the proposed theory
- Proposed a PHM framework based on entropic damage NERS

# **Thank you**

#### The team contributed to research:

- 1. Ms. Anahita Imanian (PhD Candidate)
- 2. Dr. Mehdi Amiri (Postdoc)
- 3. Mr. M. Nuhi-Faridani (Experimental support/technician)
- 4. Dr. Mohammad Modarres (Principal Investigastor)

#### Funding and oversight:

#### Office of Naval Research



